Design And Fabrication Of Components With Optimized Lattice Microstructures

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ABSTRACT:

The design and fabrication of components with optimized lattice microstructures is a new approach to creating lightweight high-performance objects. This paper introduces a unique and complete integration of design and fabrication leading to the creation of structural components with complex composite microstructures. Rather than a solid cast component with optimized outer shape this new approach leads to a component with an inner skeleton or microstructure maximizing one or more properties such as the stiffness-to-weight ratio. Three dimensional gradient materials are a natural outcome of this approach. An introduction to the design optimization and hybrid fabrication approach will be provided in addition to research progress and challenges through Spring 2004.

1. INTRODUCTION

Many biological composites have properties (strength, toughness, etc.) that are truly remarkable when compared with the properties of the constituents. Mollusk shells, for example, have high flexural strength and good fracture toughness, but they are made almost entirely of calcium carbonate. As Bond et al. [2] pointed out, imagine the possibilities if one could design a comparable composite based on high performance constituent materials. Results of the biological or evolutionary design and fabrication process are no less impressive when one considers whole components or systems. Srinivasan et al. [8] noted that biological structural systems do not distinguish between [design of] materials and structures. In other words, the large-scale structure is optimized, *and* the material from which it is made is optimized.

One goal of this project is to develop a process to integrate optimization of a structural component's shape and topology with optimization of the composite material in it, by treating the component's inner skeleton as part of the design domain. Rather than a solid cast component with optimized outer shape, for example, one could produce a component with an inner skeleton or microstructure designed to maximize the stiffness-to-weight ratio.

The second goal of this project is to develop hybrid fabrication techniques to manufacture the components with complex microstructures that result from optimized design. Solid Freeform Fabrication (SFF) has emerged as a powerful method for producing complex three-dimensional objects, so the concept of fabricating components with complex microstructures has become realistic. The current research focuses on hybrid fabrication techniques, which combine SFF with other fabrication steps such as casting and machining. The main benefit of hybrid fabrication is that it permits one to use a wide range of materials, adding each under its own ideal conditions.

The present paper describes progress made during the first year and a half of the project and some of the challenges currently facing the project team.

2. Progress and challenges in the design of optimized microstructures

The objective of structural optimization is usually to maximize the stiffness of a structure without adding weight. This is expressed mathematically as a minimization of strain energy subject to various constraints. Shape and size optimization, in which the connectivity or relationship between various parts of the object is pre-established, are becoming standard design tools for parts manufactured by casting, forging, and stamping. Topology optimization is a more general procedure; it can address connectivity and the placement of voids, and also the arrangement of material of varying density. One critique of some types of topology optimization has been that the presence of regions with intermediate densities is unrealistic. The premise of this project is that regions of varying density are not unrealistic at all — the manufacturing capabilities of SFF and Hybrid Fabrication make density variation possible.

Progress in design

Preliminary work has focused on testing concepts for the optimization process and exploring strategies for transferring the design information to the SFF machines. The structural components considered to date are limited to two-dimensional objects subjected to single in-plane load cases. All computer programs used for optimization and processing of design data have been written by the PI and an undergraduate research assistant.

The optimization procedure implemented for preliminary work follows in general the SIMP or Solid Isotropic Material with Penalization optimization [7]. The optimized design program with its finite element core is written in FORTRAN with efficient sparse matrix manipulation functions [4]. A graphic record of the optimization process is shown in Fig 1. This planar structural component is supported along the lower left edge, and subjected to concentrated loads at the upper right corner directed downward and rightward. The planar area was divided into a 100 by 100 grid of four-node plane elements. Initially all elements are given the same density. Material density was treated as the variable, and the structure's overall weight was held constant while the stiffness was maximized. The optimization process was permitted to run through only a few iterations to create a design that includes a wide range of densities. The

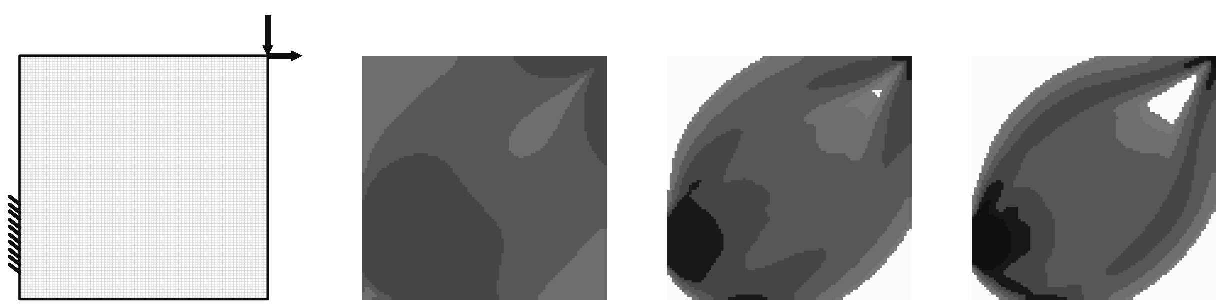

Figure 1. Topology optimization: the cantilever is fixed at the lower left corner; vertical and horizontal loads are placed at the upper right corner. High density regions are darker.

problem was re-run with a coarser mesh, with the resulting density map shown in Fig. 2.

Interpreting the density map to describe a physical object is the next step in the process. The design information was post-processed in two ways. First, the density map was interpreted as a thickness map. The resulting component, the upper right corner of which is shown in Fig. 3, could be molded, forged, or made by many other traditional fabrication techniques. Second, the density map was interpreted literally, and a microstructure was manipulated to provide the desired density. The microstructural unit cell is a three rod orthogonal lattice. The rods are rectangular in cross section, and density determines the ratio of the cross-sectional dimensions of the rods to the overall dimensions of the unit cell. The resulting component, shown partially in Fig. 4, has uniform thickness set arbitrarily at four times the unit cell dimension.

Figure 2. Density map from optimized design program.

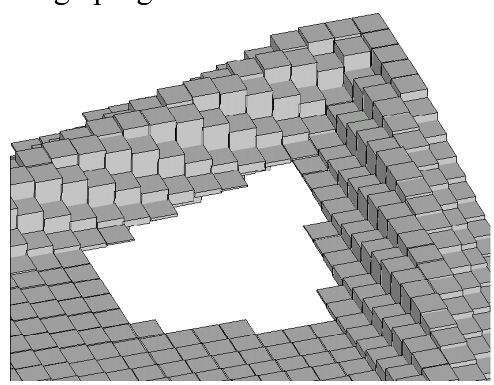

Figure 3. Interpretation of density as thickness (upper right corner of Fig 2).

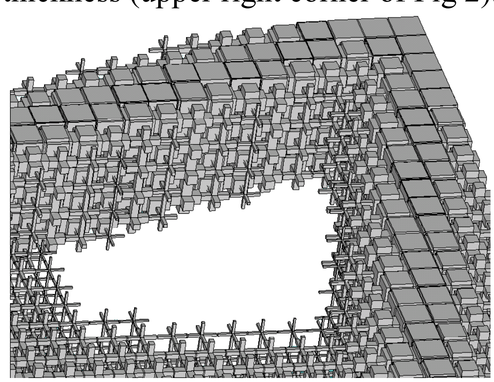

Figure 4. Microstructural interpretation of density (upper right corner of Fig 2).

One result of the design process not incorporated into the object shown in Fig. 4 is the map of principal stress directions. While imagining a procedure to re-orient the lattice elements of Fig. 4 to conform to principal stress direction, one can see that simply re-orienting the lattice units inside the existing array of rectangular cells would not work, as adjacent lattice units would no longer be aligned with one another. An entirely new array of cells —with the array aligned with principal stresses so the lattice structure will also be aligned —is required. This is analogous to a central step in adaptive finite element work, where a simple mesh is used for a preliminary analysis and then a better mesh, automatically generated from the preliminary results, is used for a refined analysis.

A second program was written by the PI to generate a new mesh of quadrilateral cells based on the optimization results. Mesh generation for this application uses, in addition to the density and principal stress direction maps, a map of principal stress direction gradient which is used to determine element size. The maps are searched numerous times during mesh generation; implementation of an “alternating digital tree” algorithm [3] to organize the information in these maps is essential for efficient searches. Automatic mesh generation follows, in general, the procedure described by Zhu et al. [10]. The resulting mesh, for the example of Fig. 2, is shown as Fig. 5. The mesh consists only of quadrilaterals, the element boundaries follow the principal

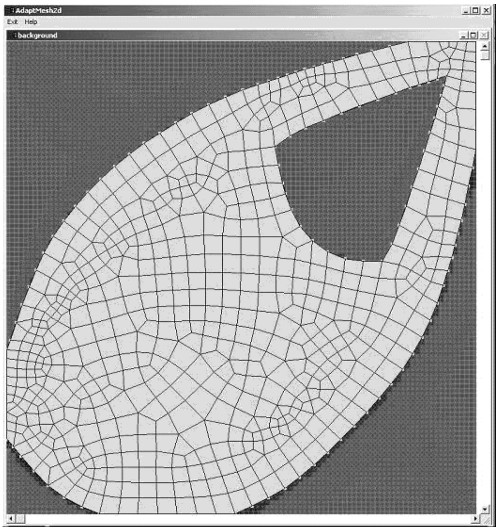

Figure 5. Automatic generation of new mesh.

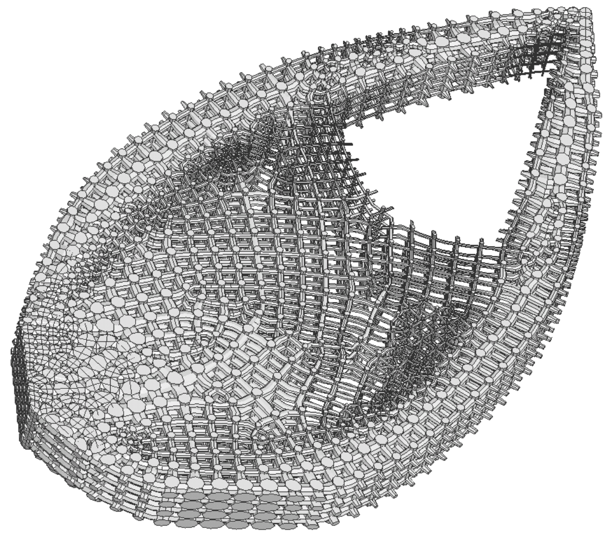

Figure 6. Resulting lattice microstructure.

stress directions (with deviations due to the constraints of creating and smoothing the quadrilaterals), and regions with sharp changes in principal stress direction have smaller elements.

A third program for manipulating the output of the optimized design program was written in C++ by an Undergraduate Research Assistant. This program requires as input the mesh shown in Fig. 5, along with information about the material density at each face of each cell. The program produces the three-rod lattice in each cell, with each rod having a regular polygon cross section and tapered to interpolate density. The output is an STL file which is the standard input to the SFF machines. The STL file, graphically represented in Fig. 6, describes the surface area of the three dimensional object as a set of triangles. Additional discussion of the use of the STL file was presented in [9].

The difference between the two interpretations of data from the optimization procedure shown in Figs. 3 and 6 is critical. The first interpretation is consistent with the current state of the art in industrial design. The varying density demanded by optimized design is interpreted as varying thickness for a nominally two-dimensional object. Because this interpretation uses the third dimension to create the effect of varying density, it could not be used to make objects with density varying in three dimensions. The second interpretation uses the microstructure to control density and orientation (and therefore the effective material properties). The third dimension is still available, so this interpretation could be used to make structural components with microstructural gradients of density, orientation, stiffness, or other effective property in three dimensions.

Current challenges in design

Having completed the algorithm development and programming for a first draft of the entire design process during the project's first year, work has turned to improving the process and making it more general. During the 2003-4 academic year attention has turned to these areas with much progress to date:

- The homogenization approach to topology optimization [1,6] is being implemented to recognize the anisotropic nature of the final design during the optimization process. Instead of a simple density map, this will produce (for two-dimensional problems) maps of lattice rod dimensions for local x and y directions.

- The MSOE Rapid Prototyping Center announced that the model of Fig. 6 broke the record for the most errors in an STL file. Fortunately the staff was able to get the Selective Laser Sintering machine to build the part. To ensure portability of designs to other SFF machines, we are developing algorithms and programming to create "error-free" STL files.
- Design for multiple load cases.
- Optimization of three-dimensional objects.

3. Progress and Challenges in Hybrid Fabrication

Hybrid fabrication is a new approach for making multi-phase composites, including functionally graded materials, by combining the most advantageous aspects of SFF and conventional fabrication techniques. Here the critical geometric feature of the composite is intertwining two or more three-dimensional lattices, thus each phase of the composite is continuous and separate from the other phases. SFF is used to create the initial framework for the intertwined lattices, and then the solid materials for each phase are added as separate steps as shown in Fig. 7 [5]. Hybrid synthesis of intertwined lattices avoids problems that can occur when multiple materials are directly formed in a SFF process by combining two or more powder types within a melt-pool. One such problem is the creation of multiple metallurgical grain microstructures and porosity. Another challenge is dealing with varied material melting points, delivery systems, and buoyancy of ceramic reinforcements. By separating the materials into lattices and creating one lattice phase at a time using hybrid fabrication, the metallurgical challenges are avoided; each material can be processed under its own ideal conditions.

Progress in hybrid fabrication

Currently, there are no standard hybrid synthesis procedures for generating complex lattice structures with features smaller than 1 mm, so a starting point for this project was to consider a large number of SFF-based hybrid casting "paths" and combinations of steps. Metal casting techniques such as centrifugal casting were experimented with, leading to concerns and questions about quantifying the quality of castings and limitations of select casting processes. With no standards for comparing the potential of hybrid fabrication paths a standard benchmarking system was developed.

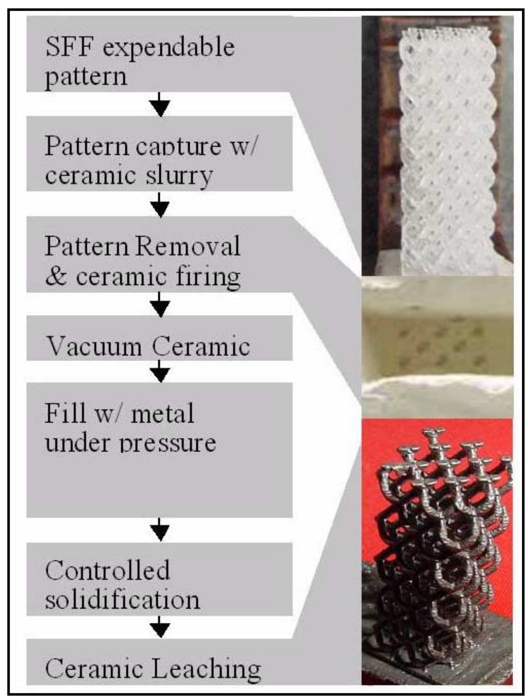

Figure 7. Example Hybrid Fabrication Process

Evaluation of a number of hybrid paths, on paper and experimentally, has led to a list of hybrid fabrication requirements as follows: the complete transferal of the expendable mold material around (and into) very fine features of the expendable pattern without trapping gas or forming voids; complete removal of the expendable pattern without damaging the mold; ceramic mold firing without cracking, sagging, or breakage; pattern removal without residue in □unvented dead-ends□ and fine mold features; complete mold fill with metal without damaging or eroding the mold geometry; complete mold filling with metal before freezing; overcoming surface tension of molten metal to fill features finer than 1 mm; elimination of gas defects in casting due to trapped gasses; control of the direction of solidification to reduce solidification shrinkage defects; prevention of buoyancy force damage on delicate, high aspect ratio, features.

The development of a new hybrid fabrication process has begun, with preliminary results producing castings with features approaching 0.05 mm. The process is similar to that illustrated schematically in Fig. 7. This approach has good potential to meet the aforementioned requirements including resolution capabilities and ability to be processed in a vacuum. Several breakthroughs in ceramic processing, pattern removal and metal casting have resulted in the casting of very fine features, such as those of the fractal tree shown in Fig. 8.

Figure 8. Finely detailed casting □ a result of hybrid fabrication..

To evaluate potential hybrid fabrication processes, the effect of each processing variable on the quality of the finished part must be assessed. To accomplish this, several benchmark parts were developed. An example is shown at the top of Fig. 9; this part examines minimum feature size of lattice rods. Fig. 9 also shows results of a hybrid process similar to that shown in Fig. 7 for features representing rods on the final metal casting.

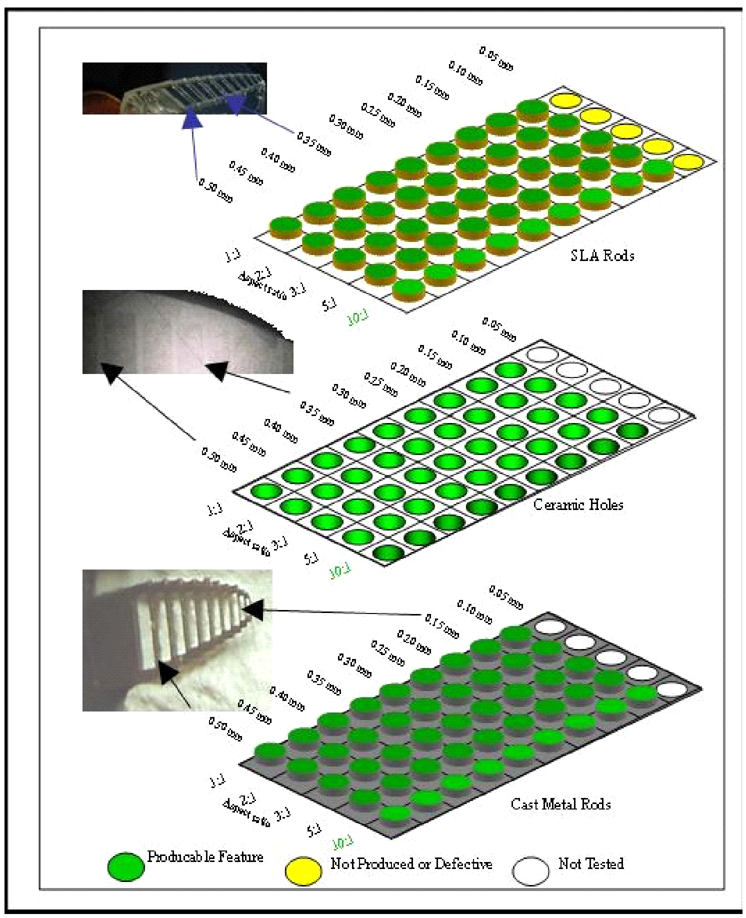

Figure 9. Benchmarking results for hybrid fabrication □ casting of metal with fine holes.

Current challenges in hybrid fabrication

With one practical hybrid fabrication path selected and a method to measure capability and improvement the research focus has been directed to a number of new challenges for the 2003-2004 academic year with significant progress in the first three areas:

- Completion of testing and debugging of the hybrid fabrication process shown in Fig. 7.

- Removal of the expendable mold material after casting without damaging the casting.
- Reduction of risk of the expendable mold cracking or failing during metal pressurization.
- Begin the evaluation of mechanical properties as a function of lattice element feature size and comparison of mechanical properties to wrought properties.

4. CONCLUSIONS

The progress made during the first year and a half of work on this project suggests that this research will lead to practical procedures for the design and fabrication of lightweight, high performance structure and machine parts. The key to these new procedures is the further development of hybrid fabrication techniques to allow production of components with complex optimized microstructures. Significant hurdles remain in both the design and fabrication halves of the project.

5. ACKNOWLEDGMENTS

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